APPLICATION OF RADIOGRAPHY TO CERTAIN TEST WELDS

by

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INTRODUCTION

The development of non-destructive testing methods and the recently improved fusion welding processes of important engineering structures go hand in hand toward paving the road to great advancement in modern engineering design and construction. The many variables that accompany the fusion process of welding create a condition that demands a non-destructive test of the welded joint. The majority engineering opinion considered that such a test is necessary before fusion welding can be generally applied to engineering structures, such as power boiler drums and oil cracking equipment where high pressures and temperatures are used.

Hodge (1936) stated:

> The control testing of a material or structural unit is generally accomplished by destructively testing representative samples. The evaluation of a material can not, of course, be obtained by this general method if wide variations in quality are present in a lot of material to be tested. This being particularly true if the material contains, in haphazard distribution, gross defects such as cracks or other discontinuities which may not be revealed by visual inspection of the surface of the material. The presence of discontinuities in some engineering materials has led to the necessity for their detection, this being accomplished by some non-destructive testing method.

The most common types of non-destructive testing are the radiographic, magnaflux, stethoscopic, and the visual inspection. Radiographic examination is becoming the most

widespread of the non-destructive tests in commercial use today. Briefly the test consists of obtaining a "shadow graph" of the "body" of a weld or casting, using an X-ray beam as the "shadow" producing agent and a photographic plate as the recording device. By this method it is possible to obtain an "image," on a photographic plate, of all discontinuities or lack of homogeneity, such as gas pockets or slag inclusions whose magnitude is two per cent or greater of the plate thickness.

During the past year, a radiographic machine was installed in the Department of Shop Practice at Kansas State College of Agriculture and Applied Science to complement the destructive testing machines already in use on the welding and casting work of the department. This "Wappler" mechanical rectification unit has a kilovolt peak (kvp) rating of 160 and, with the aid of intensifying screens, is capable of successfully radiographing castings and welds up to two inches in thickness. The machine is proving very satisfactory since the average thickness of material seldom exceeds one inch.

HISTORY

During the ceremonies at Wurtsburg in 1896, Roentgen officially proclaimed his discovery of the X-ray and at that

time prophesied the now common science of industrial radiography (Roentgen, 1897). But there were many obstacles in the road of the early pioneers. It soon became evident that high voltage and long exposures were necessary for the successful radiography of metals. During the first decade of the twentieth century, the science of X-ray therapy became prevalent and higher voltage equipment was needed. The development of these high voltage units made available more powerful apparatus for the industrial radiologist.

The one step that was outstanding in the progress of radiography was the invention and development of the filament controlled Coolidge tube. Twenty-five years ago, Cooldige, of the General Electric laboratories, perfected this tube which is in universal use today and which made possible the delicate control of output intensities thus simplifying the problem of voltage and thickness relationships. (Clark, 1932.)

During 1928 and 1929 the American Society of Mechanical Engineers was formulating rules for the fusion welding of high pressure vessels, and the non-destructive testing of these welds was one of the requirements of the code even before a practical method of testing procedure had been investigated. In the early part of 1930, X-ray apparatus was installed by the inspection department of one of the promi-

nent boiler makers. In 1931 the radiographic method was required for the testing of the fusion process of welding which was formally adopted by the A.S.M.E. boiler code, covering the construction of high pressure vessels. A census taken in 1936 stated that there were at least 40 X-ray equipments in this country, and during the past two years there has been a continued increase. (Hodge, 1936.)

EXPERIMENTAL PROCEDURE

Theory

The general law for the absorption of X-radiation may be expressed,

$$I = I_0 e^{-\mu x} \tag{1}$$

or $$\log \frac{I}{I_0} = -\mu x \tag{2}$$

where I is the transmitted intensity of the beam and I_0 is the incident intensity, or the intensity leaving the X-ray tube. μ is the linear absorption coefficient for the average wave length of the X-radiation, and x is the distance traversed through the object. Loeb (1938) has graphed mass

absorption, which is linear absorption divided by the density, versus atomic number for hard and soft rays. This graph is reproduced in Figure 1.

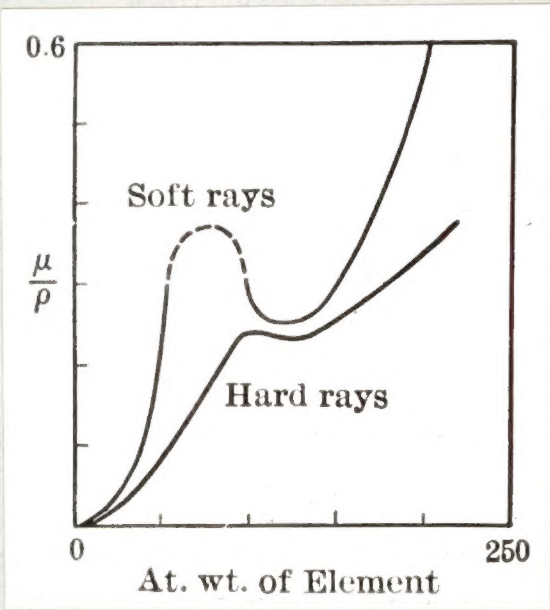

Fig. 1. X-ray absorption.

From the graph it may be shown that

$$\mu \propto \frac{Z}{V^n} \tag{3}$$

where Z is the atomic number and V is the peak voltage and n has a value from two to three. In other words the absorption of the X-ray beam is proportional to the density of the "absorber" and inversely proportional to the average wave length of the beam.

A convenient form for the conversion of voltage to wave length may be expressed as

$$\lambda(\text{wave length}) = \frac{12345}{V} \qquad (4)$$

where lambda is in Angstrom units (1 A.U.=10^{-8} cm.). From a consideration of equations (3) and (4) it is understood why gamma and cosmic rays have such highly penetrative ability, since these rays have very short wave lengths.

For best results the X-ray intensity striking the film should have a minimum value of ten per cent of the incident beam. Using this assumption and knowing the thickness, x, the approximate voltage for the exposure can be obtained from the absorption curves. But in actual practice it is not possible to rigidly apply these equations, since the X-ray beam is made up of numerous wave lengths of radiation having different absorption coefficients. Also, for a given beam of X-rays entering an object the coefficient of absorption will change as the radiation progresses, since the first layers of metal will filter out the soft rays, leaving the harder ones which have a lower absorption coefficient to continue through the metal. This problem may be reduced by making the beam more homogeneous by full wave rectification

of voltage and the use of filters.

Factors Affecting the Radiographic Procedure

Choice of voltage. It was mentioned above that an intensity of at least ten per cent of the main beam was necessary for sensitization of the photographic plate or radiograph. It is evident then, that in order to get the maximum number of possible shades between the lightest and darkest areas, the proper voltage must be chosen which will allow minimum transmissability of the X-ray beam on the thickest section of the metal radiographed. In other words radiation intensity striking the film has a range from ten to one hundred per cent of the incident beam, according to the amount of metal it has traversed.

Intensifying screens. Intensifying screens as the name implies are used to magnify the effect of the X-rays in sensitizing the film. These screens, in general, are made of calcium tungstate, which is a fluorescent material. Under the influence of X-rays, this calcium tungstate fluoresces with a deep blue light that is strongly actinic. The fluorescence of the screen is directly proportional to the X-ray intensity striking the material. This proportionality is quite fortunate and no doubt is one of the outstanding discoveries which reduce the exposure period to a minimum.

The fluorescent material is mixed with a binder and formed into a flat screen in such a manner that the film can be placed against it. Intimate contact is necessary in order to assure the absence of any spreading of the blue light as it leaves the screen which would cause an enlargement of the apparent "image." Laboratory tests have shown that these screens will intensify the sensitization of the film as much as 100 times. (Clark, 1932.) For average shop conditions the intensification is about thirty, depending upon the type and age of the screens.

Penetrameters. Artificial defects, which are placed on the surface of the specimen to measure the sensitivity of the exposure are called penetrameters. One common type consists of a metal plate having a thickness of two per cent of the thickness of the object to be radiographed and of the same material. Holes, of various diameters, are drilled in this penetrameter, the image of which should appear on the radiograph if the exposure has the proper sensitivity. Likewise, images on the radiograph of the same degree of darkness as the penetrameter holes, indicate the defects, represented by these images, are of the same order of magnitude. Knowing the size of the defects is very essential, and because of this the A.S.M.E. boiler code requirements

call for the use of penetrameters in the production radiography of high pressure vessel welding.

Dark room. The design of a radiographic dark room does not differ considerably from that of an ordinary photographic dark room. A lead lined box for film storage is necessary where X-ray or gamma ray work is being done. Over a long time the accumulated effect of the radiation will fog the unprotected film until it is useless. This situation becomes aggravated when the X-ray source and the dark room are close to each other. Other dark room problems are similar to those encountered in ordinary photography.

Interpretation of radiographs. After obtaining the radiograph it is important that the "images" on the film be interpreted properly. This might be done to a high degree of accuracy by the use of a photometer, but such practice is completely impractical for shop work, under present conditions. By devising a light background of uniform intensity, the radiographs can be studied and interpreted by eye with a rather high degree of accuracy. In most radiographs there are "land marks" that indicate the sensitivity of the exposure. For instance, the splatter due to the welding process will be "imaged" on the film, and will serve as an index to the magnitude of the internal defects in certain cases. Here, as in many other fields, improved accuracy

comes with experience and familiarity with radiography. Just as every shadow on a radiograph of the human body has a significance to the medical radiologist, so too, every spot on the film has a significance in the eyes of the industrial radiologist.

Experimental Data

Methods and materials. One hundred test coupons were prepared for radiographic and tensile impact testing. All of these coupons were made from mild steel stock except the group from 60 to 70 which were made from certified mild steel. These coupons were welded out of 3/8 by 3/4-inch bars, using special jigs for mounting during the welding operation. The weld was of the double vee type, butt joint, using a No. V Lincoln coated electrode and performed by an operator of laboratory welding experience. Radiographs were taken in the "as welded" condition before the samples were prepared for the tensile impact test. These radiographs appear in Plates I, II, and III. The progressive steps in the preparation of the coupons for the tensile impact test are shown in Figure 3 of Plate V. The coupons were X-rayed again as they appear in the condition for tensile impact testing indicated in the next to the last step in Figure 3 of Plate V. The reproduction of this second group of radio-

graphs appears in Plates III and IV. These radiographs were interpreted and qualified as "good" or "bad" and recorded as indicated in Table 1. Likewise tensile impact tests were run and the mechanical properties of the welds were tabulated in Table 1.

<u>The tensile impact test</u>. The tensile impact test was decided upon as providing the best comparison with the radiographic test as to the effect of lack of homogeneity resulting from the welding operation. The tensile impact test measures the physical qualities of the <u>volume</u> of the metal in the parallel section under stress. Therefore, qualities of the test section are affected considerably by the presence of slag inclusions and gas pockets. The radiographic test, at present, is capable only of indicating this lack of homogeneity due to gas pockets or slag inclusions.

<u>Interpretation of data</u>. Knowing the sensitivity of a given radiograph, it was possible to estimate the size of the defects. In the given radiographed coupons only the center section is of concern since the sides are removed in the machining operation preparatory to the tensile impact test. From previous observation of the effect of defects in test bars it was possible to predict where the failure would occur. A comparison of the radiographs in Plates I, II, and III with the destructive test values in Table 1 will bring

out this point.

Out of the 100 test bars, the position of failure was predicted in all cases except two. In several cases failure occurred in the parent metal albeit there were defects in the deposited metal. This indicated the increased strength of deposited metal over parent metal.

The graph shown in Figure 4 is a plot of tensile impact values versus per cent elongation. As is readily evident, the test specimens are separated into two general groups. One group comprises those that failed in the deposited metal section while the other group represents the failures in the parent metal section. Due to the lower ductility of the deposited metal, failures in this area are brittle and show little reduction in area. Figure 2, Plate V, exemplifies this statement.

DISCUSSION

Radiographs

Criticisms of radiographs. Since there is no accepted standard for interpreting radiographs, an individual criterion must be set up in the mind of the radiologist. This criterion, of course, is determined by the quality of weld demanded.

Modern practice demands almost a complete absence of discontinuities in certain engineering structures. Therefore, a radiograph showing any defects whatsoever will indicate a "bad weld." However, as is shown in the test samples, the radiograph will reveal defects and still represent a weld of greater than 100 per cent efficiency. It was this last criterion that served in interpreting the radiographs as representing "good" or "bad" welds. These criticisms were made before the destructive tests were run, and appear in the last column of Table 1. Where the observation was incorrect, as indicated by the destructive test, the remark was placed in quotation marks.

Industrial demands upon the radiologist have caused him to increase the sensitivity of the radiograph. It has been common practice to obtain a sensitivity of two per cent in routine work while the radiographs made in this test work had a sensitivity of one per cent. A well known motor car plant in Detroit seeks a sensitivity of one half of one per cent in the radiography of crank shafts. This degree of sensitivity, for instance, allows small flaws to be detected which could not be noticed otherwise, until the final grinding operations on the bearings.

<u>Location of failure</u>. It is interesting to note that there was not a single failure in the heat affected area of

the welds. The rupture either occurred in the cross section of the defect, or in the unaffected area of the parent metal. These types of failure are shown in Figure 2 of Plate V.

Advantages of Radiographic Testing

Flexibility. In the radiographic test no machine work is necessary. Exposure ratings are determined for the given thickness of metal and the specimen exposed in the "as welded" condition. The dark room procedure is simple and soon becomes routine. The radiograph also serves as a permanent record for future reference concerning exposure ratings and the quality of the weld.

Cost. While radiographic work, at present, is expensive, and without it certain modern engineering structures would not be practical, there is no non-destructive test that can replace it. Successful attempts are being made to reduce the cost of radiographic tests.

SUMMARY

The results of the tests recorded in the previous pages may be summarized as follows:

1. Out of 100 tested coupons the radiograph indicated the correct failure position in all but two cases.

2. Failure occurred either in the deposited metal or in the unaffected area of the parent metal. There were no failures in the heat affected area.

3. The radiographs showed a sensitivity of one per cent as indicated by the penetrameters.

4. Many welds that were shown as defective in the radiograph did not fail in the weld metal. The tensile impact strength of the deposited metal was greater than the parent metal strength.

5. The radiographic test was much superior to the tensile impact test concerning actual time consumed in running the tests.

ACKNOWLEDGMENT

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Table 1. Correlation of tensile impact values with radiographic interpretation. Mild steel stock used.

Coupon	Diameter	Tensile impact	Elongation	Reduction area	Radiographic interpretation
No.	Inches	Ft. lb.	Per cent	Per cent	
1	.312	38	14.0	11.2	Bad
3	.311	32	10.9	9.2	Bad
4	.311	32	6.8	9.0	Bad
5	.310	36	4.2	7.5	Bad
6	.311	104	25.0	40.8	Good
7	.311	36	10.0	10.4	Bad
8	.310	96	27.3	44.0	"Bad"
9	.310	25	1.5	4.8	Bad
10	.311	38	6.2	14.0	Bad
11	.310	90	15.6	14.7	Bad
12	.311	54	10.9	8.5	Bad
13	.310	52	9.3	7.1	Bad
15	.310	42	9.5	13.2	Bad
16	.312	40	10.0	13.1	Bad
17	.311	40	12.5	11.6	Bad
19	.310	100	21.0	42.7	Good
21	.311	44	10.9	12.0	Bad
22	.310	78	14.0	11.1	Bad
23	.311	82	17.2	21.2	Bad
24	.311	132	30.5	40.3	Good
25	.311	84	37.8	15.1	Bad
26	.311	142	22.1	56.4	Good
27	.310	28	5.5	4.2	Bad
31	.310	90	31.2	36.5	Good
32	.311	54	6.2	11.9	Bad
33	.311	146	28.1	55.6	Good
34	.310	38	8.8	10.6	Bad
35	.310	86	17.2	39.7	Bad
36	.310	90	14.1	9.5	Bad
37	.311	152	28.1	37.2	Good
38	.310	158	30.4	40.2	Good
39	.309	78	12.5	11.0	Bad
40	.311	40	10.9	12.8	Bad
41	.311	158	28.1	41.8	Good
42	.312	170	21.2	39.0	Good

Table 1 (cont.)

Cou-pon No.	Diam-eter Inches	Tensile impact Ft. lb.	Elonga-tion Per cent	Reduction area Per cent	Radio-graphic interpre-tation
43	.311	78	16.3	8.8	Bad
44	.310	152	28.1	40.0	Good
45	.310	124	25.0	42.0	Good
46	.308	0	0.0	0.0	
47	.310	44	12.5	14.0	Bad
48	.311	68	12.5	13.6	Bad
49	.312	104	28.1	42.5	Good
50	.309	136	28.1	38.5	Good
51	.312	80	12.5	11.9	Bad
52	.311	76	15.3	11.2	Bad
53	.312	164	28.1	37.5	Good
54	.309	58	9.4	10.0	Bad
55	.311	106	28.1	38.0	Good
56	.312	98	25.0	44.0	Good
57	.312	182	31.2	42.6	Good
58	.311	172	31.2	39.0	Good
59	.312	172	28.3	36.0	Good
60	.312	100	18.7	41.0	Good
61	.312	130	21.9	12.7	"Bad"
62	.312	144	28.1	30.5	Good
63	.311	140	28.1	38.5	Good
64	.312	172	31.2	38.0	Good
65	.310	140	28.0	40.0	Good
66	.311	44	9.4	12.3	Bad
67	.312	162	28.1	37.0	Good
68	.311	170	31.2	39.1	Good
69	.311	106	31.2	38.6	Good
70a	.310	162	28.1	38.0	Good
70	.312	149	28.1	42.8	Good
71	.311	104	33.5	44.0	Good
72	.312	96	21.9	42.2	Good
73	.312	126	28.0	40.3	Good
74	.311	156	29.7	35.0	Good
75	.311	158	28.1	40.5	Good
76	.309	166	31.2	38.4	Good
77	.310	128	28.4	39.3	Good
78	.313	82	12.5	11.6	Bad
79	.312	104	25.0	43.4	Good

Table 1 (concl.)

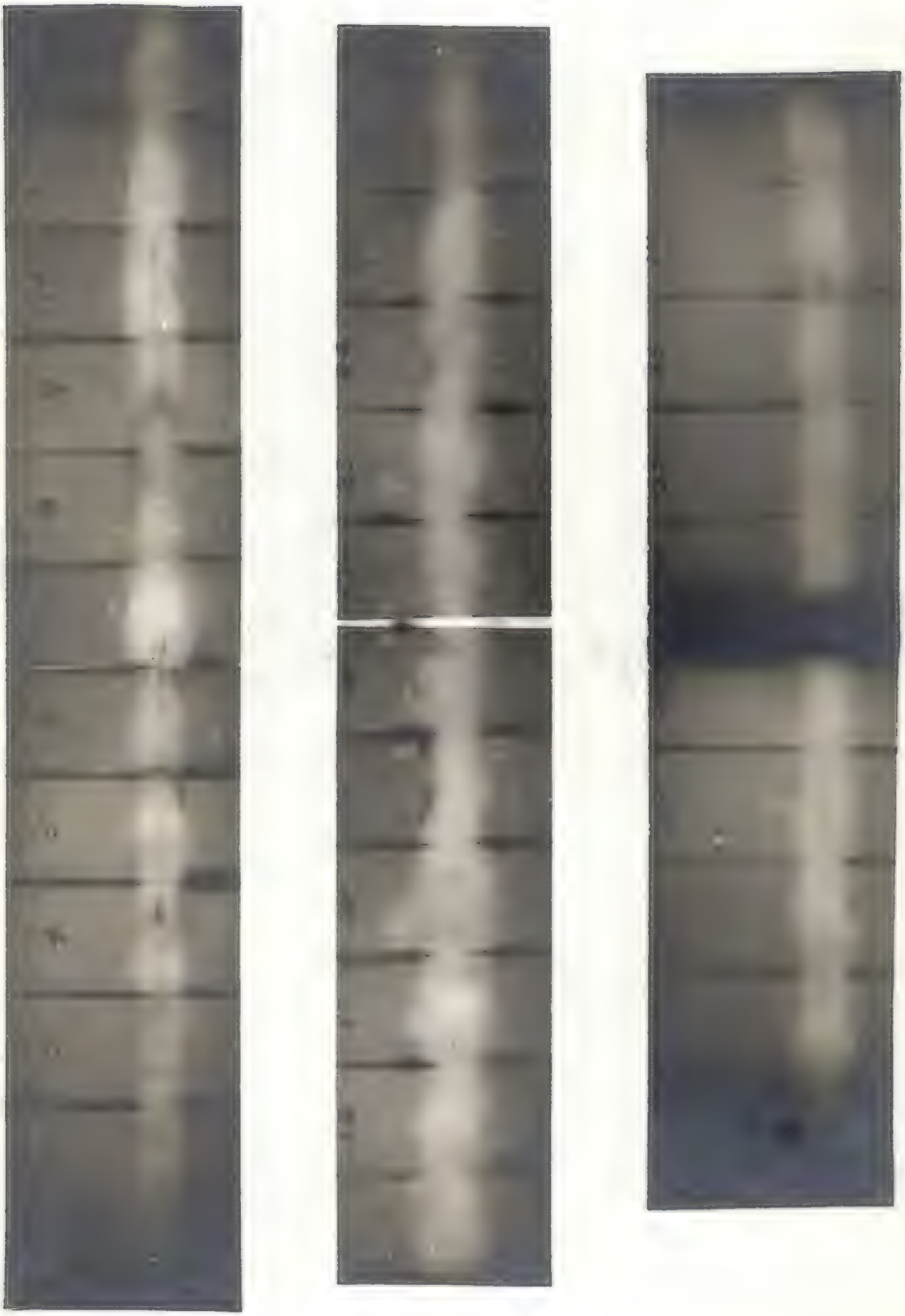
Coupon No.	Diameter Inches	Tensile impact Ft. lb.	Elongation Per cent	Reduction area Per cent	Radiographic interpretation
80	.311	166	27.2	29.1	Good
82	.312	96	22.4	43.6	Good
83	.312	130	31.6	35.3	Good
84	.312	124	25.0	36.0	Good
85	.311	128	25.0	39.5	Good
86	.311	70	9.4	5.2	Bad
87	.309	58	6.2	6.9	Bad
88	.312	42	7.1	12.2	Bad
89	.311	146	29.1	37.2	Good
91	.312	148	28.1	39.2	Good
92	.310	140	28.0	35.5	Good
95	.312	143	28.1	37.6	Good
96	.311	152	29.7	42.1	Good
97	.312	146	28.1	35.7	Good
98	.311	143	28.1	39.1	Good
99	.306	144	30.4	37.2	Good

EXPLANATION OF PLATE I

The exposure settings for these radiographs were:

Voltage	110 kvp.
Amperage	6 ma.
Time	15 sec.
Focal-film distance	40 in.
Intensifying screens	Patterson Industrial.
Filters	0.62 in. Al.

PLATE I

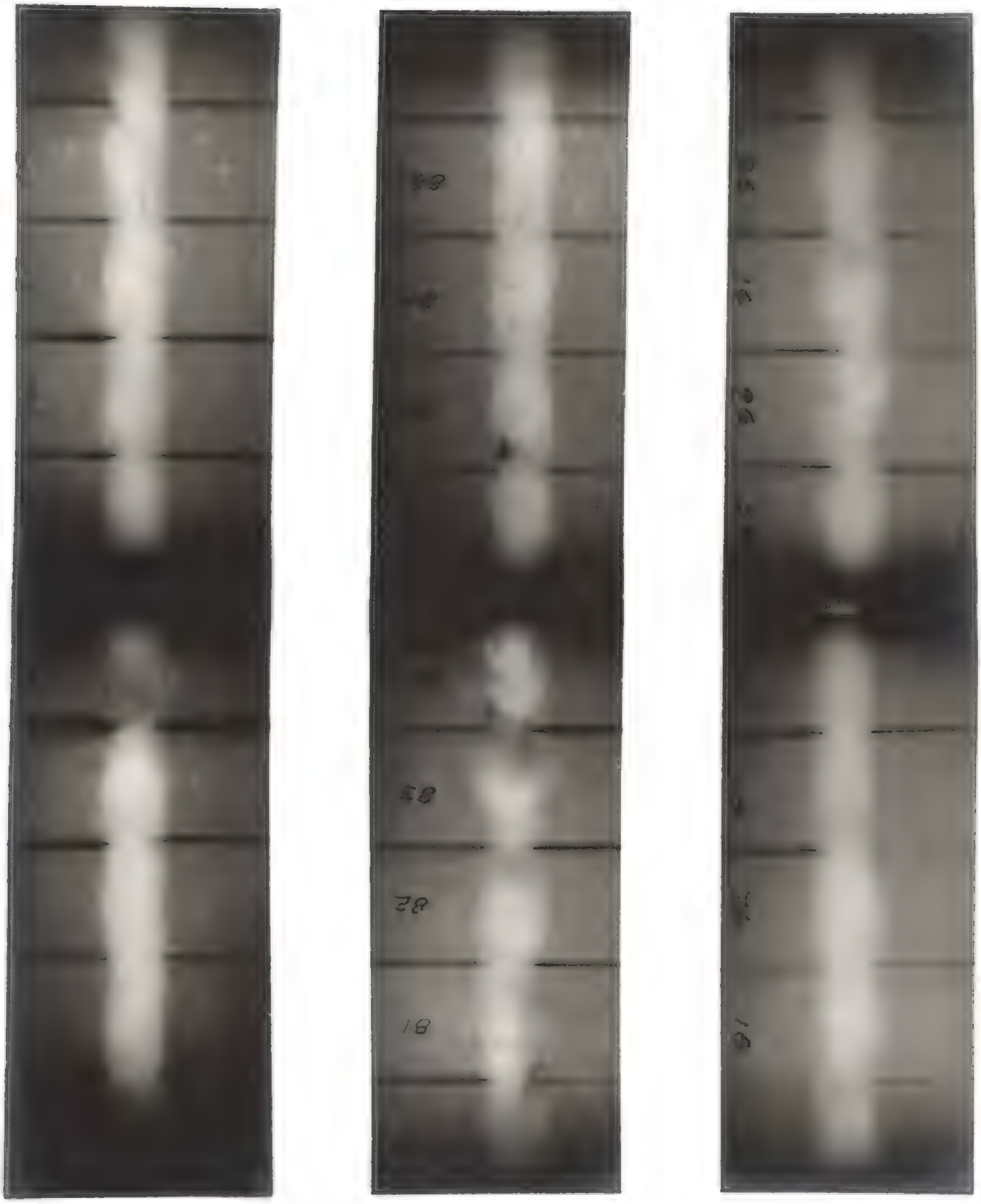


EXPLANATION OF PLATE II

The exposure settings for these radiographs were:

Voltage	110 kvp.
Amperage	6 ma.
Time	12 sec.
Focal-film distance	40 in.
Intensifying screens	Patterson Industrial.
Filters	0.62 in. Al.

PLATE II



EXPLANATION OF PLATE III

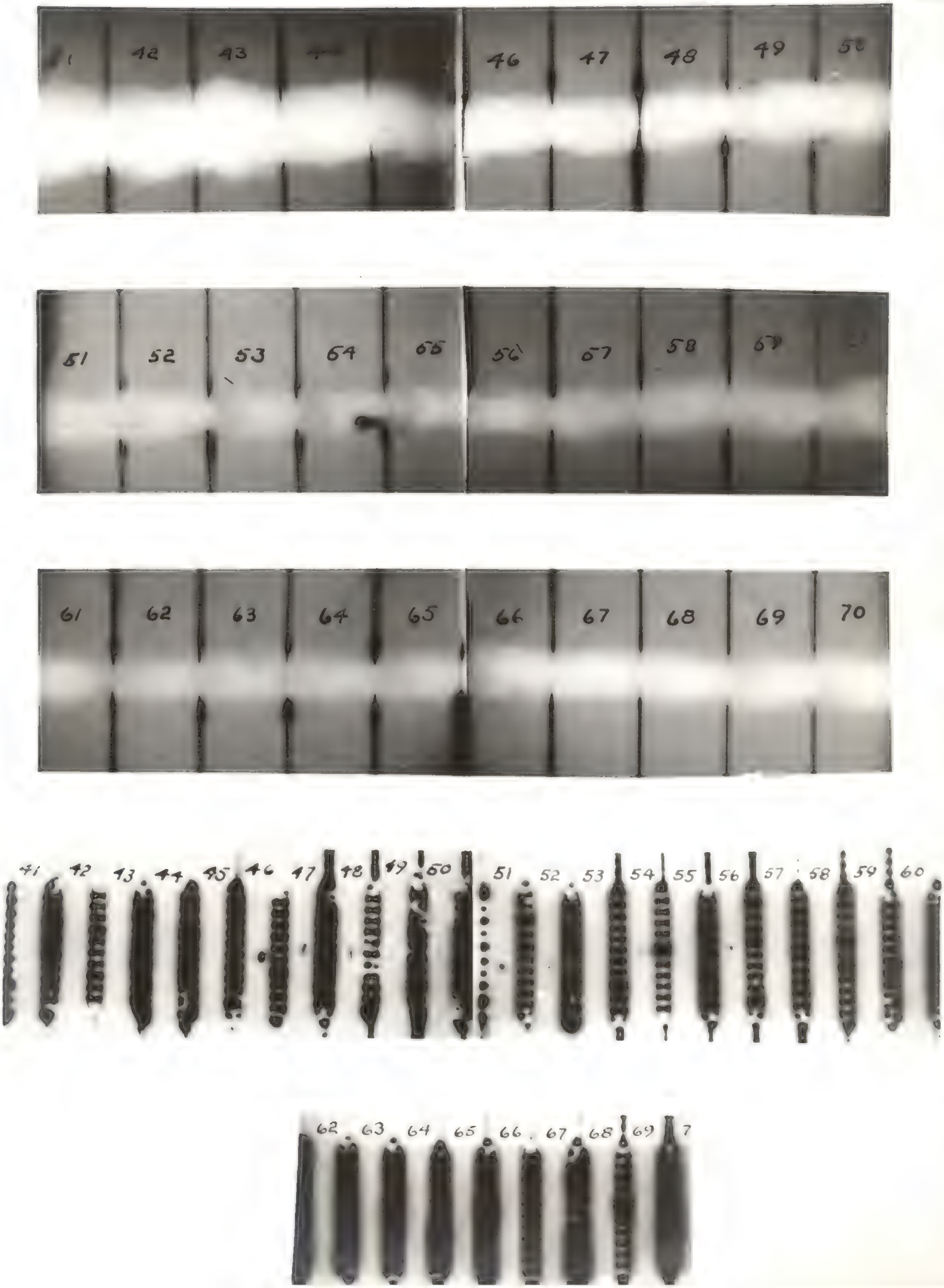
The exposure settings for these radiographs were:

Voltage..................................110 kvp.
Amperage.................................. 6 ma.
Time..................................... 15 sec.
Focal-film distance...................... 40 in.
Intensifying screens.....Patterson Industrial.
Filters..........................0.62 in. Al.

and

Voltage...................................90 kvp.
Amperage.................................. 6 ma.
Time......................................15 sec.
Focal-film distance...................... 40 in.
Intensifying screens.....Patterson Industrial.
Filters..........................0.62 in. Al.

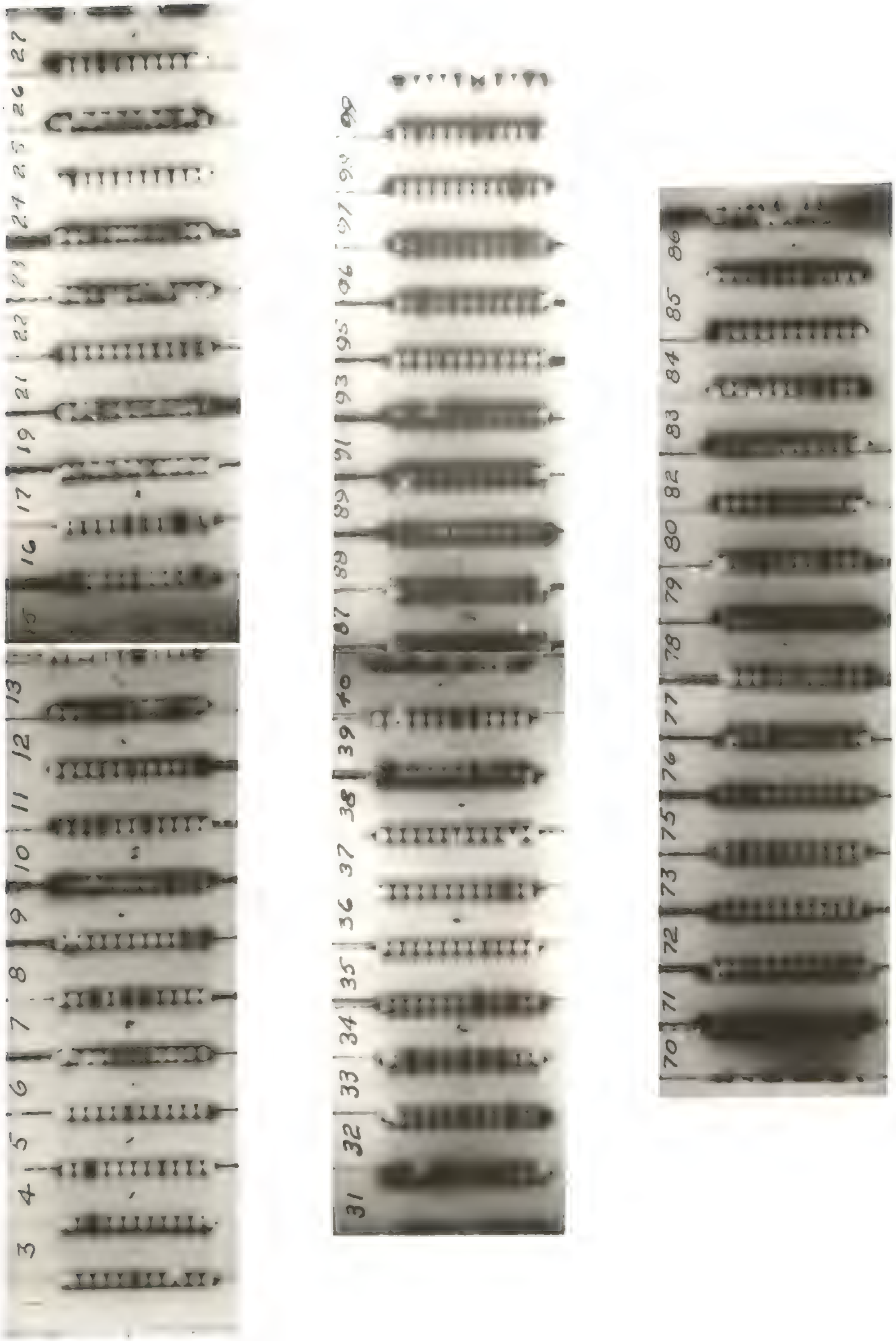
PLATE III


42 43 46 47 48 49
51 52 53 64 65 57 58
61 62 63 64 65 66 67 68 69 70
41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
62 63 64 65 66 67 68 69

EXPLANATION OF PLATE IV

The exposure settings for these radiographs were:

Voltage..................................60 kvp.
Amperage.................................. 5 ma.
Time......................................15 sec.
Focal-film distance....................... 40 in.
Intensifying screens.....Patterson Industrial.
Filters..............................0.02 in. Al.



EXPLANATION OF PLATE V

Fig. 2. Representative samples of ruptured specimens. The two failures on the left are weld metal ruptures, while the failure on the right is a parent metal rupture.

Fig. 3. The progressive steps in the preparation of coupons for the tensile impact test. Radiographs were taken of the coupons as they appear in the first and fourth steps.

Fig. 2

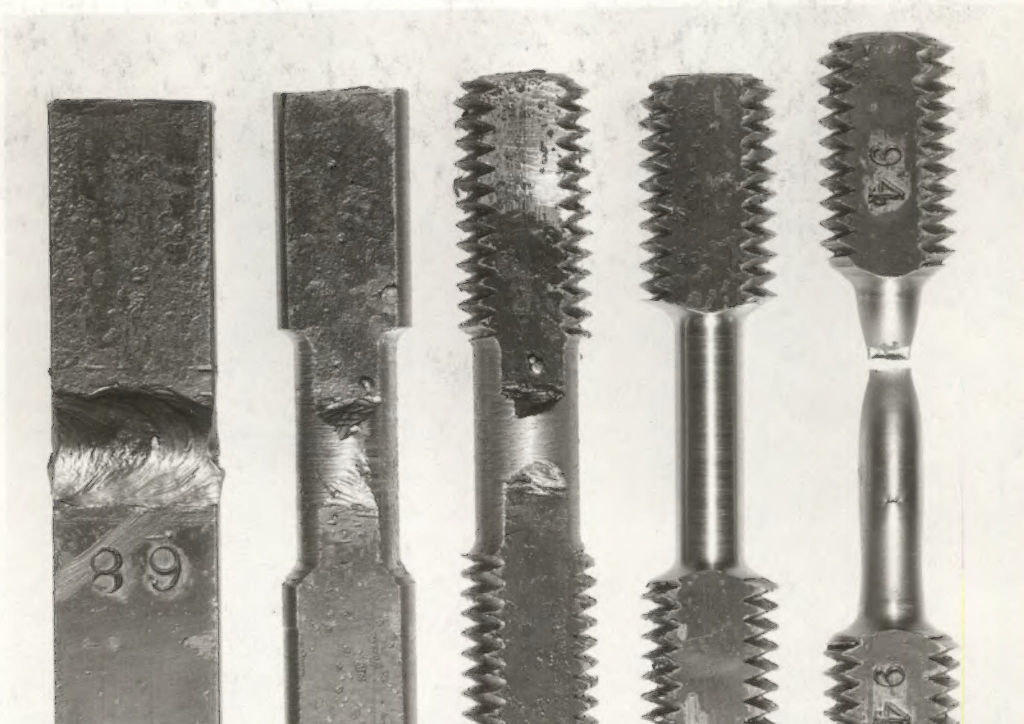
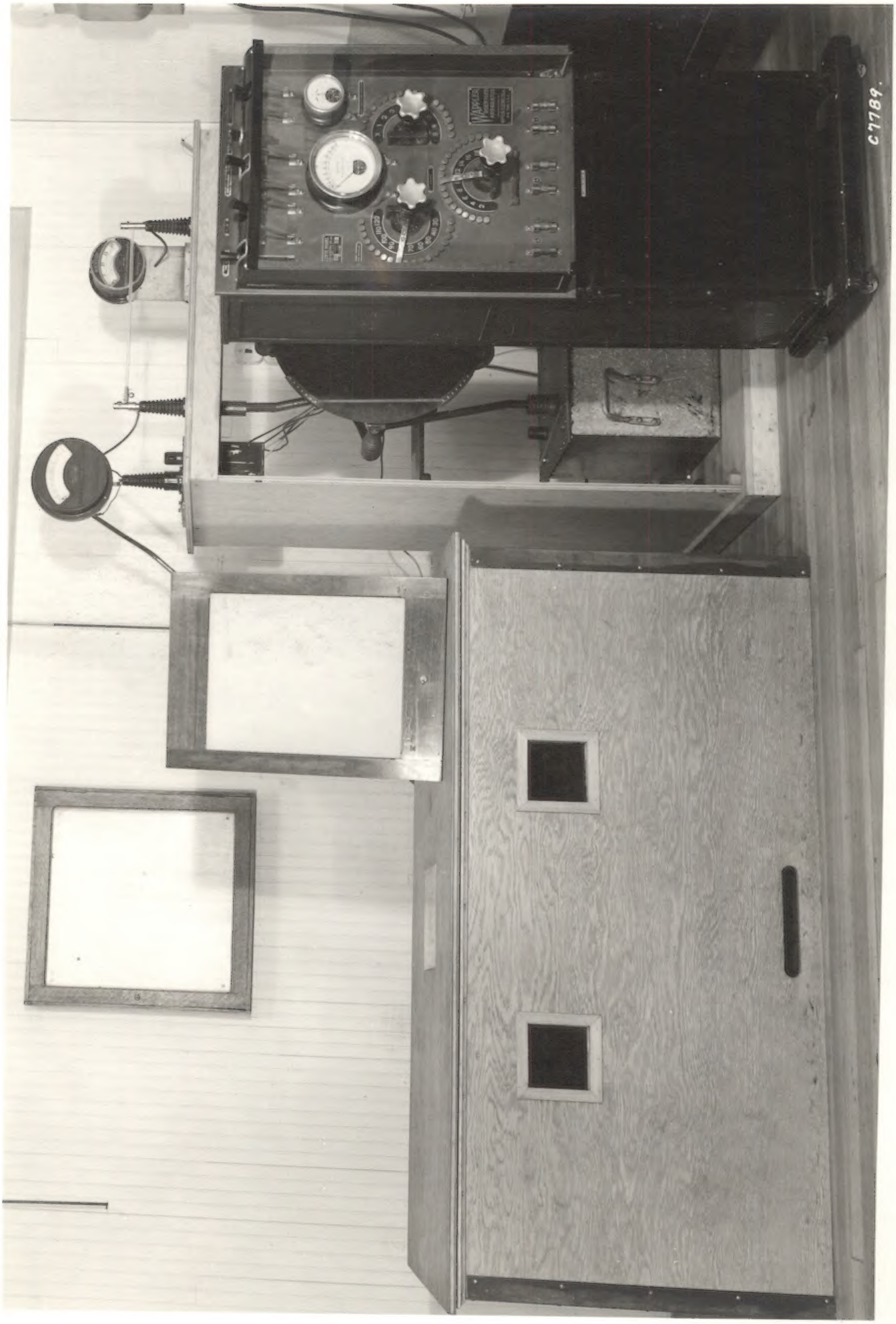


Fig. 3

EXPLANATION OF PLATE VI

A general view of the entire X-ray machine. The lead-lined box on the left contains the X-ray tube. The light box for examining radiographs is seen on the top of the box. Samples to be radiographed are placed above the aluminum filter in the center of the top of the box.

PLATE VI



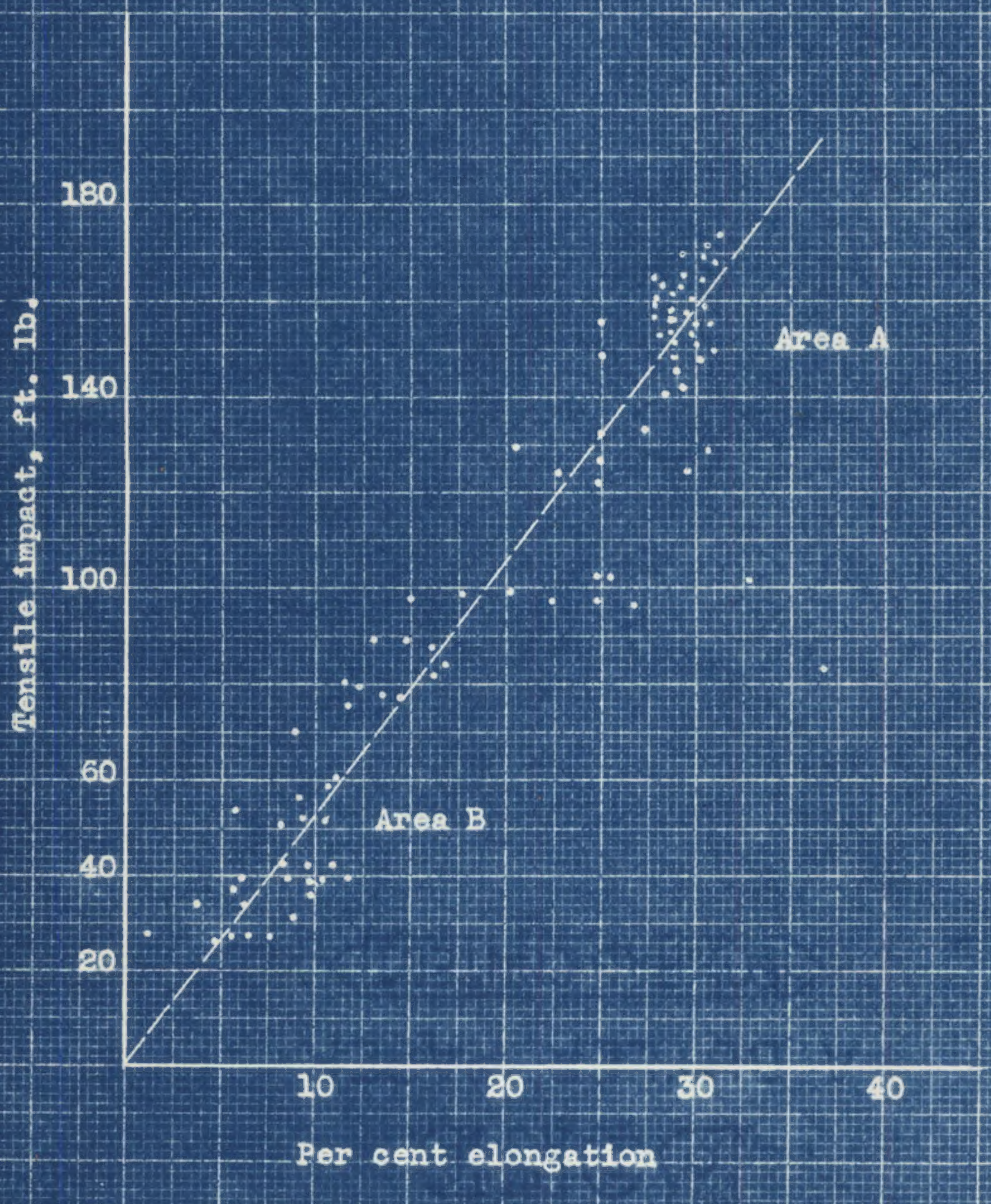


Fig. 4. Showing relationship between parent metal failures (Area A), and weld metal failures (Area B).